Enhanced vortex damping by eddy currents in superconductor-semiconductor hybrids

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Abstract

An enhancement of vortex-motion damping in thin Pb/In superconducting films is obtained through coupling to an adjacent two-dimensional electron gas formed in a modulation-doped GaAs/AlGaAs heterostructure. This effect is observed by monitoring the power dissipation at the superconductor in the vortex state while increasing the density of the electron gas using a gate voltage. Quantitative agreement is found with calculations based on a viscous model of vortex damping which considers generation of eddy currents in the electron gas by moving flux lines. In the regime of filamentary and channel vortex flow, eddy-current damping leads to striking dissipation breakdown due to stopping of entire vortex channels.

71.10.Ca, 73.50.-h, 74.60.Ge, 74.76.Db

Superconductor-semiconductor hybrid structures are emerging as key devices in the search for new physical phenomena resulting from interactions between two systems with dissimilar electronic properties[1]. In particular, Josephson-type junctions with Nb electrodes coupled by a two-dimensional electron gas (2DEG) in InAs layers exhibit phase-sensitive transport due to Andreev reflections of quasi particles at the interfaces between normal metal and superconductor[2–4]. Other experiments concentrate on commensurability and interference effects on electron ballistic transport in the 2DEG, which occur when a perpendicular magnetic field is spacially modulated by the vortices of an adjacent superconducting film. In this case, a pronounced suppression of the Hall effect was observed and ascribed to electron diffraction by flux quanta[5].

Few investigations are concerned with the influence of a normal metal on the vortex dynamics under a transport current, although the devices were intentionally designed to have no viscous coupling[6]. One can think of our hybrid system as a modified Giaever's dc transformer[7], in which one of the superconducting films has been replaced by a 2D electron gas. Under the action of a Lorentz force the vortices move at constant velocity due to viscous damping. For an isolated superconductor, this damping originates from the voltage induced across the normal core of each moving vortex. By bringing a highly mobile electron gas close enough to the superconducting film, i.e. at a distance of the order of the London penetration depth, an additional dissipation mechanism is introduced through magnetic coupling resulting in an increase of viscosity. An interesting issue is to what extent this would affect filamentary and channel vortex flow, for which dissipation jumps are observed in the current-voltage curves[8–10]. The study of vortex damping in hybrids may provide further insight into vortex-vortex interactions and pinning effects.

This Letter reports the first observation of damping enhancement for vortex motion due to the presence of a high-mobility electron gas in superconductor-semiconductor hybrids. The samples used in our experiments consist of thin Pb/In

films evaporated on top of modulation-doped GaAs/AlGaAs heterostructures. The evidence is found in the decrease of dissipation voltage measured at the superconducting film due to a higher viscosity for vortex flow in the hybrid system, as compared to the case without the 2DEG beneath. We vary the normal metal conductivity by increasing the carrier density using a gate voltage applied between the 2DEG and a back contact. Our results are in quantitative agreement with the predictions of a model which accounts for the generation of eddy currents in the electron gas by flowing vortices. For an estimated increase in electron density of up to 20% the relative change observed in dissipation voltage lies in the one-percent range. For the currents and magnetic fields at which filamentary vortex flow occurs, however, striking dissipation reductions are readily achieved.

The semiconductor component of the hybrid system is either a 25 nm wide GaAs/AlGaAs single quantum well (SQW) or a single heterointerface (SHI) structure. A two-dimensional electron gas is realized by modulation doping and is buried at a distance $D = 75$ nm and 50 nm from the surface for the SQW and SHI structure, respectively[11]. The nominal mobilities and carrier densities of both samples at 4.2 K and under illumination are $\mu \simeq 8 \times 10^5\,\mathrm{cm}^2/\mathrm{Vs}$ and $n \simeq 5.6 \times 10^{11}\,\mathrm{cm}^{-2}$. The electron gas is contacted from the surface by In alloying in order to apply a gate voltage U_g between it and a metallic back contact. The variation of the 2D density was examined previously in photoluminescence experiments[12]. A linear increase in the carrier density $n_{2\mathrm{D}}$ between its nominal value and at most $\sim 6.5 \times 10^{11}\,\mathrm{cm}^{-2}$ can be achieved by applying a gate voltage between 0 and 200 V. Hence the estimated maximum possible increase of density is less than 20%. Superconducting films of Pb with nominally 14 at.% In were evaporated on the semiconductor surface (4×4 mm^2) with film thicknesses d ranging from 60 to 300 nm, as determined using atomic-force microscopy. The superconducting transition in zero field occurs at 7.2 K. For transport experiments, Au leads were pressed against the superconductor film. Current-voltage measurements were performed with standard four-terminal configuration using dc currents up to 1.5 A. Experiments were carried out at 4.2 K

and low perpendicular magnetic fields $B < 0.2$ T.

To model the coupling between vortex lattice and electron gas in our hybrid samples we consider the effect on the normal metal of the magnetic field B of a moving vortex with speed v. The experimental situation is schematically shown in the inset to Fig. 1. Flowing vortices induce an electric field in the 2DEG that generates eddy currents leading to an additional dissipation which, in turn, forces the fluxoids to slow down. In the limit $D \ll \lambda^2/d$ of small superconductor-2DEG distances as compared to the effective London penetration depth, the magnetic field of a vortex can be approximated as $\mathbf{B} \sim (\Phi_0/2\pi\lambda^2)K_0(r/\lambda)\hat{z}$, where $\Phi_0 = h/2e$ is the flux quantum and K_0 the zeroth-order Bessel function of imaginary argument[13]. For our samples the effective penetration depth is five to eight times D[8]. The vector potential in the plane of the 2DEG can be written as

$$\mathbf{A}(\rho) = \frac{\Phi_0}{2\pi\rho} F(\rho/\lambda)\hat{e}_\varphi, \tag{1}$$

where ρ is the polar radius from the vortex core, and $F(x) = \int_0^x dy\, y K_0(y)$.

The time-varying vector potential produced by a flowing vortex induces an electric field $\mathbf{E} = v\,\frac{\partial}{\partial x}\mathbf{A}(x - vt, y)$, which causes joule dissipation in the 2D gas. The energy loss per unit time is calculated according to

$$\frac{d\varepsilon}{dt} = \sigma_{\mathrm{2DEG}} v^2 \int d^2x \left[\frac{\partial}{\partial x}\mathbf{A}(\rho/\lambda)\right]^2 \simeq \frac{\Phi_0^2}{2\pi\lambda^2}\sigma_{\mathrm{2DEG}} v^2 \equiv \eta_{\mathrm{2DEG}}\, v^2, \tag{2}$$

where σ_{2DEG} is the conductivity of the 2D electron gas and the dimensionless integrals are assumed to be of the order of one.

We arrive at the general result that eddy current generation in the hybrid system manifests itself in a contribution to the viscosity η_{2DEG} describing the enhanced damping of vortex motion. This effect can be observed if η_{2DEG} is comparable to the viscosity of type-II superconducting material, $\eta_{\mathrm{SC}} = \sigma_n d\, \Phi_0^2/2\pi a^2$[14], where σ_n is the normal state conductivity of the superconductor and a the vortex core radius. The electron gas acts as a shunt conductor, thus increasing the system viscosity $\eta_{\mathrm{tot}} = \eta_{\mathrm{SC}} + \eta_{\mathrm{2DEG}}$ by a factor

$$1 + \frac{\eta_{\rm 2DEG}}{\eta_{\rm SC}} = 1 + \left(\frac{a}{\lambda}\right)^2 \frac{\sigma_{\rm 2DEG}}{\sigma_n d}. \tag{3}$$

Hence the dissipation voltage under a transport current is $U_d \propto v^{14}$ and the vortex velocity is determined by the balance between the driving force jB and the viscous drag ηv. Eddy-current damping grows in proportion to $\sigma_{\rm 2DEG}$, i.e. to the carrier density $n_{\rm 2D}$ of the electron gas.

The dissipation due to flowing vortices in the PbIn superconducting film is reduced by increasing the charge density in the neighboring electron gas. Figure 1 shows a typical dissipation voltage (U_d) versus gate bias (U_g) curve of a PbIn/SHI hybrid sample measured at a constant transport current of 600 mA. Sweeping U_g from 0 to 170 V causes a linear decrease in dissipation of $\Delta U_d = 0.022$ mV, i.e. ~ 0.1 % of the initial value. Since optical and transport experiments could not be carried out simultaneously, we give here the gate voltage as a measure of the electron density which we assume to vary linearly with U_g, as inferred from optical measurements[12]. We emphasize that in spite of the relatively small change in 2DEG density the coupling within the hybrid appears to be effective enough to show up in its dissipative behavior. We also notice that during the experiment no leakage current between superconductor and electron gas was ever detected, thus we rule out any spurious bias to be at the origin of the observed effect.

We interpret the dissipation change in the superconductor with rising charge density in the 2DEG as the effect of eddy currents in the electron gas which slow down the vortices causing the voltage across the superconductor to decrease. Using Eq. (3) we can now estimate the magnitude of this effect. Taking $a \approx \lambda$, $d \approx$ 100 nm, $\sigma_n \approx 1.4 \times 10^5\,\Omega^{-1}\text{cm}^{-1}$ as obtained from resistance measurements, and $\sigma_{\rm 2DEG} \approx 0.08\,\Omega^{-1}$ with the 2DEG parameters given above, this yields $\eta_{\rm 2DEG}/\eta_{\rm SC} \approx$ 5%. This change in dissipation voltage corresponds to the difference between having and not having the electron gas next to the superconductor. In our experiments, however, we start from a finite density and produce a variation of about 10%. Thus, the calculated dissipation change is around 0.5%, in very good agreement with the

experimental results.

Eddy-current damping effects are much more pronounced in the regime of filamentary and channel vortex flow, for they can lead to a striking fall of dissipation voltage by more than one order of magnitude, as shown in Fig. 2. Here, U_d was measured at a current close to the repinning transition of a large vortex channel. The inset to Fig. 2 displays the IV characteristic of the superconducting film measured for a field of 53 mT and at 4.2 K but without gate bias. The abrupt jumps and large hysteresis apparent in the IV curve are the signature of channel vortex flow[8]. As indicated by the arrow, the point where the measurement of dissipation versus gate voltage was carried out is close above the critical current at which the downward jump occurs. In this case, the vortex speed is just high enough for the channel to keep flowing. Energy loss due to eddy currents slows the vortices further down, so that the whole channel will eventually be repinned. When the vortex channel stops, dissipation suddenly drops. This process is irreversible since, as can be seen in Fig. 2, dissipation does not resume to its initial value when the gate voltage is swept back to zero. This effect is highly reproducible even after heating the sample over T_c and re-cooling.

The study of the dependence on gate voltage of the current values at which dissipation jumps occur provides further information about the nature of filamentary vortex flow and the role played by pinning. Figure 3 shows one example in which the currents for the upward and downward voltage jumps are plotted as a function of gate bias (the corresponding IV curve is displayed in the inset to Fig. 3). The jump-up current is independent of the 2D density indicating that the pinning strength is not appreciably affected by the presence of the electron gas. In contrast, the jump-down current increases with U_g. With increasing viscosity the vortices of a moving channel slow down such that its repinning occurs at larger values of the transport current. This is interpreted as additional evidence of a repinning force which depends on vortex velocity. A similar increase in jump-down current is observed for thin PbIn

films on glass by decreasing the external magnetic field[8].

The influence of magnetic field homogeneity on eddy-current damping is revealed by the percentage change in dissipation as a function of magnetic field at constant transport current. As a measure of the damping strength, the maximum dissipation change ΔU_d for a gate voltage interval of $\Delta U_g = 170$ V is normalized by the dissipation voltage U_{d0} at zero bias. The corresponding values measured at 500 mA and 1000 mA are shown in Fig. 4 as a function of the external magnetic field B. At $B \leq 30$ mT damping causes 0.1–0.2 % change in dissipation. At 40 mT, the data for both 0.5 A and 1 A display a sharp maximum and become very small at fields larger than 50 mT, where the resistance of the film is close to normal but the transport behavior is characterized by massive vortex flow.

The weakening of the effect of eddy-current damping on dissipation with increasing magnetic field (solid line in Fig. 4) can be explained as due to the growing homogeneity of the field pattern of the vortices while approaching the upper critical field B_{c2}. At low magnetic fields, i.e. low vortex density, the field distribution is very inhomogeneous, since B has a maximum at the vortex cores dropping to zero between them. Thus, $\dot{B}$ is large and damping is efficient. When vortices start to overlap, the lateral modulation of magnetic field in the plane of the 2DEG is continuously reduced. As a consequence, eddy currents as well as damping effects are weak. In contrast, the peak at 40 mT is associated with the enhancement of the effects due to eddy-current damping in the regime dominated by filamentary vortex flow. Here the dissipation change is greatly enhanced by fluctuations in the number of moving vortices contributing to dissipation due to the depinning and repinning of a large number of small vortex filaments in quick succession.

In summary, we have observed significant additional damping of vortex motion in superconductor-semiconductor hybrid systems. A theoretical model is used to calculate the damping effect from eddy currents generated in the 2D electron gas showing quantitative agreement with the experiment. Under conditions of filamentary vortex

flow, the energy loss due to eddy currents leads to the stopping of entire channels, such that power dissipation in a hybrid device can be switched off by slightly increasing the electron density. At large fields damping is weak due to the vanishing lateral field modulation in the plane of the 2DEG. We point out that, although our observations can be explained within the framework of classical electrodynamics, novel effects due to quantization of the electron gas conductivity are anticipated to occur for the conditions of the experiments. Our results provide further insight into the issue of vortex dynamics with dissipation and open up a new class of devices for the study of correlations between adjacent non-tunneling systems with dissimilar electronic and magnetic properties.

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FIGURES

Fig. 1. Dissipation voltage as a function of gate bias of a PbIn/SHI hybrid structure in a magnetic field of 53 mT and at 4.2 K. The transport current was 600 mA. The inset shows a sketch of the hybrid sample. I is the transport current. The arrow represents a flux line with magnetic field B moving at a speed v.

Fig. 2. Dissipation voltage as a function of gate bias of a PbIn/SHI hybrid structure in a perpendicular magnetic field of 53 mT for 500 mA current and at 4.2 K. The inset shows the corresponding current-voltage characteristic. The point where the measurement of dissipation versus gate voltage was taken is marked with an arrow.

Fig. 3. Dependence on gate voltage of the critical current for the upward (up triangles) and the downward voltage jump (down triangles) for a PbIn/SQW hybrid at 4.2 K and at a magnetic field of 71 mT within the region of channel vortex flow. The inset shows the corresponding IV characteristic.

Fig. 4. Dissipation percentage change versus magnetic field for a PbIn/SQW hybrid sample at 4.2 K. Data were taken at 500 mA (solid symbols) and 1000 mA (open symbols). The solid line is a guide to the eye. The shaded area indicates the field range within which voltage jumps are observed for the used currents.

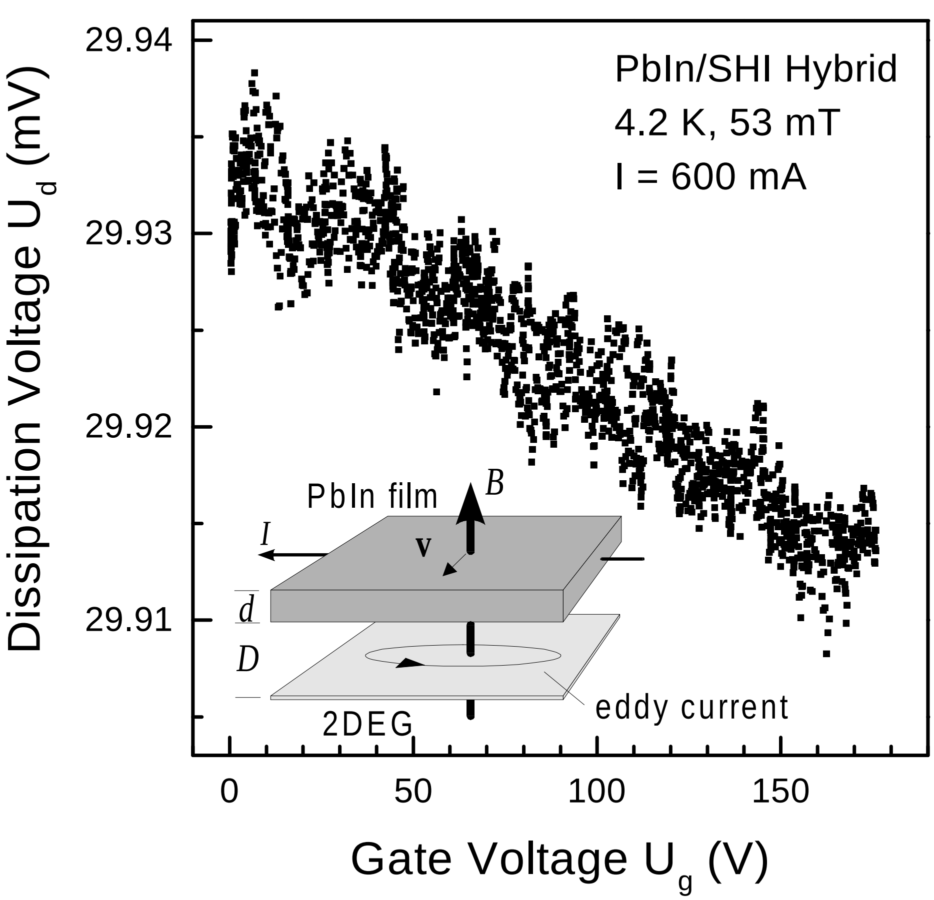

Fig. 1   Danckwerts et al.

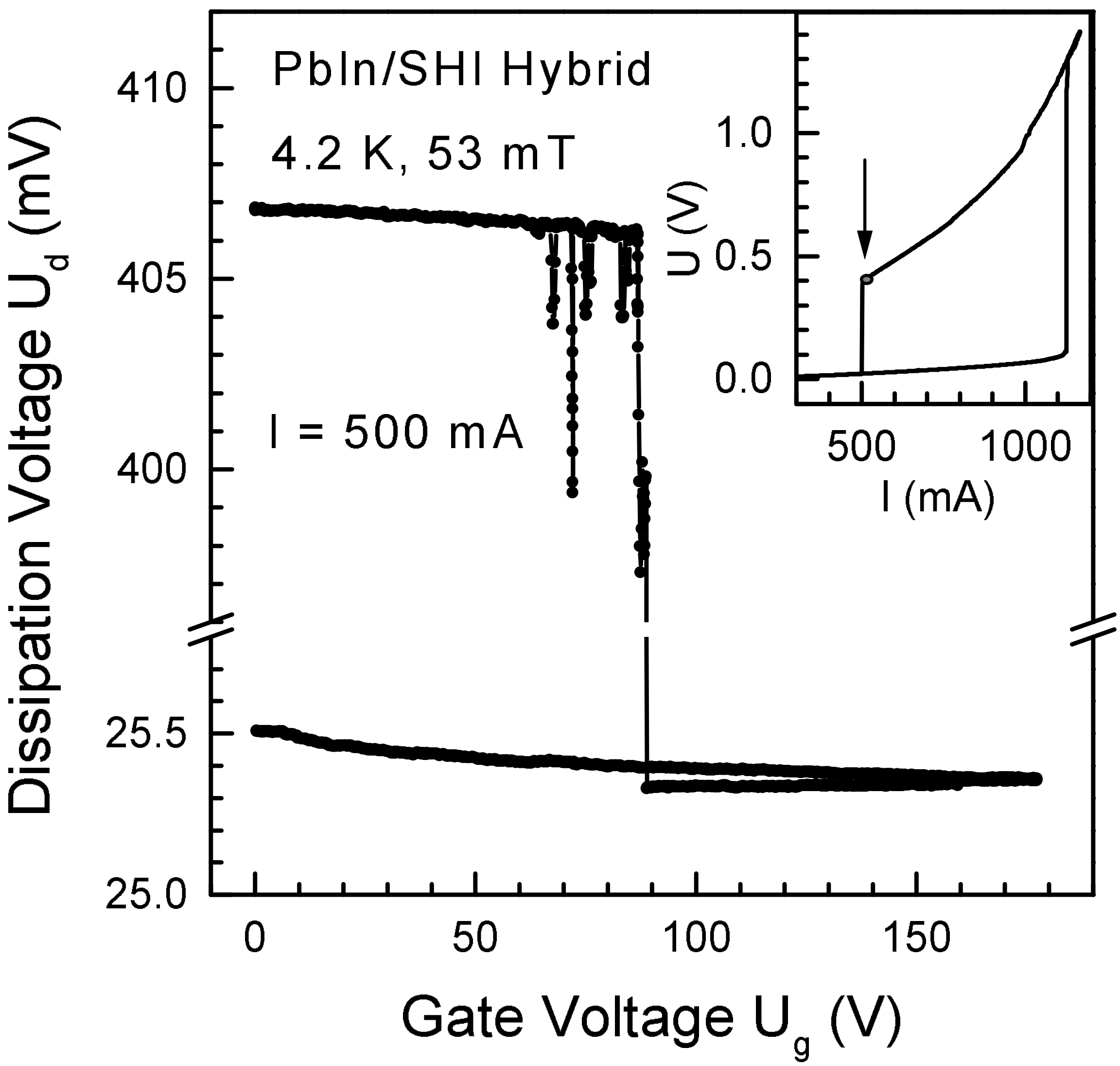

Fig. 2

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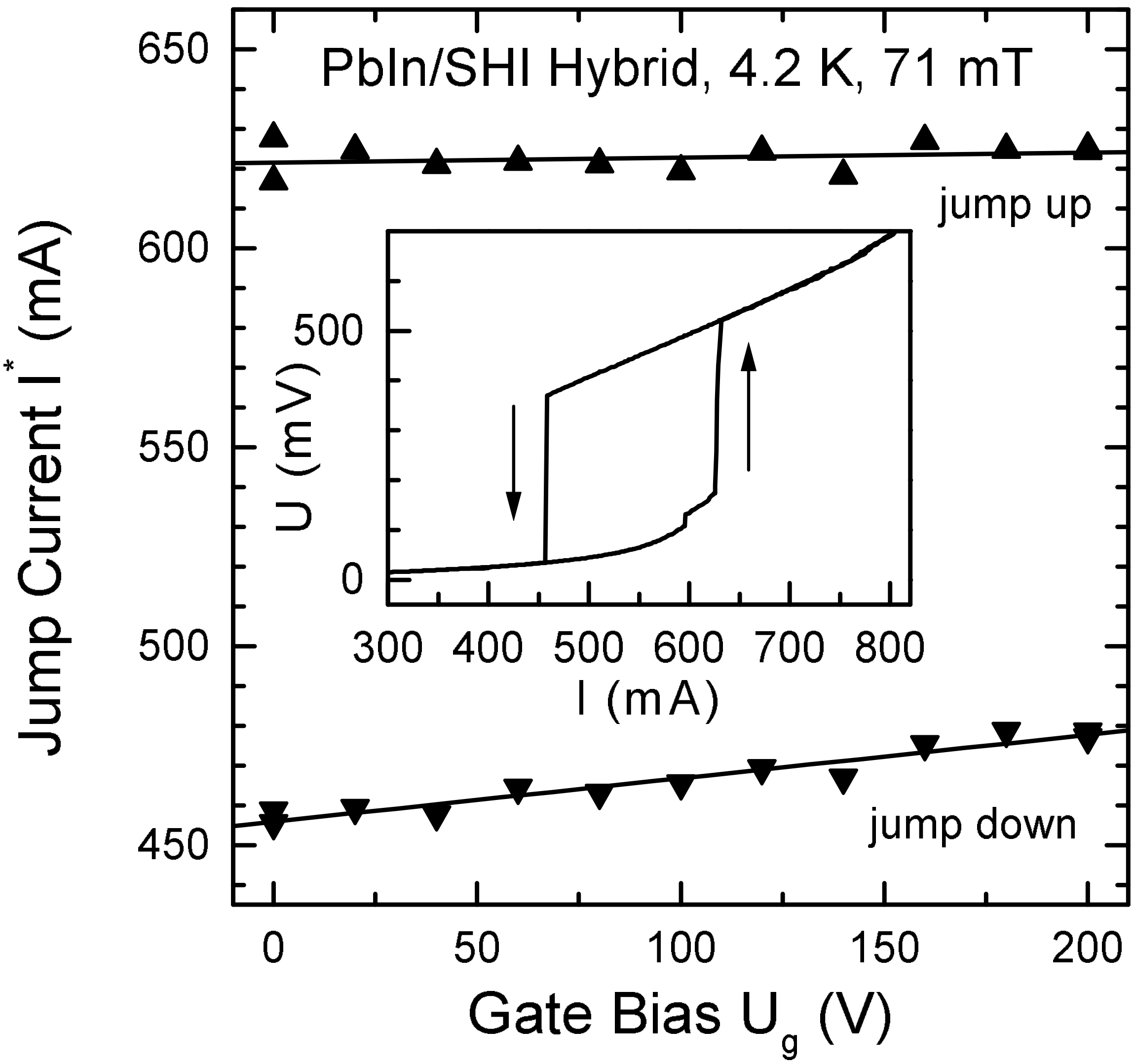

Fig. 3

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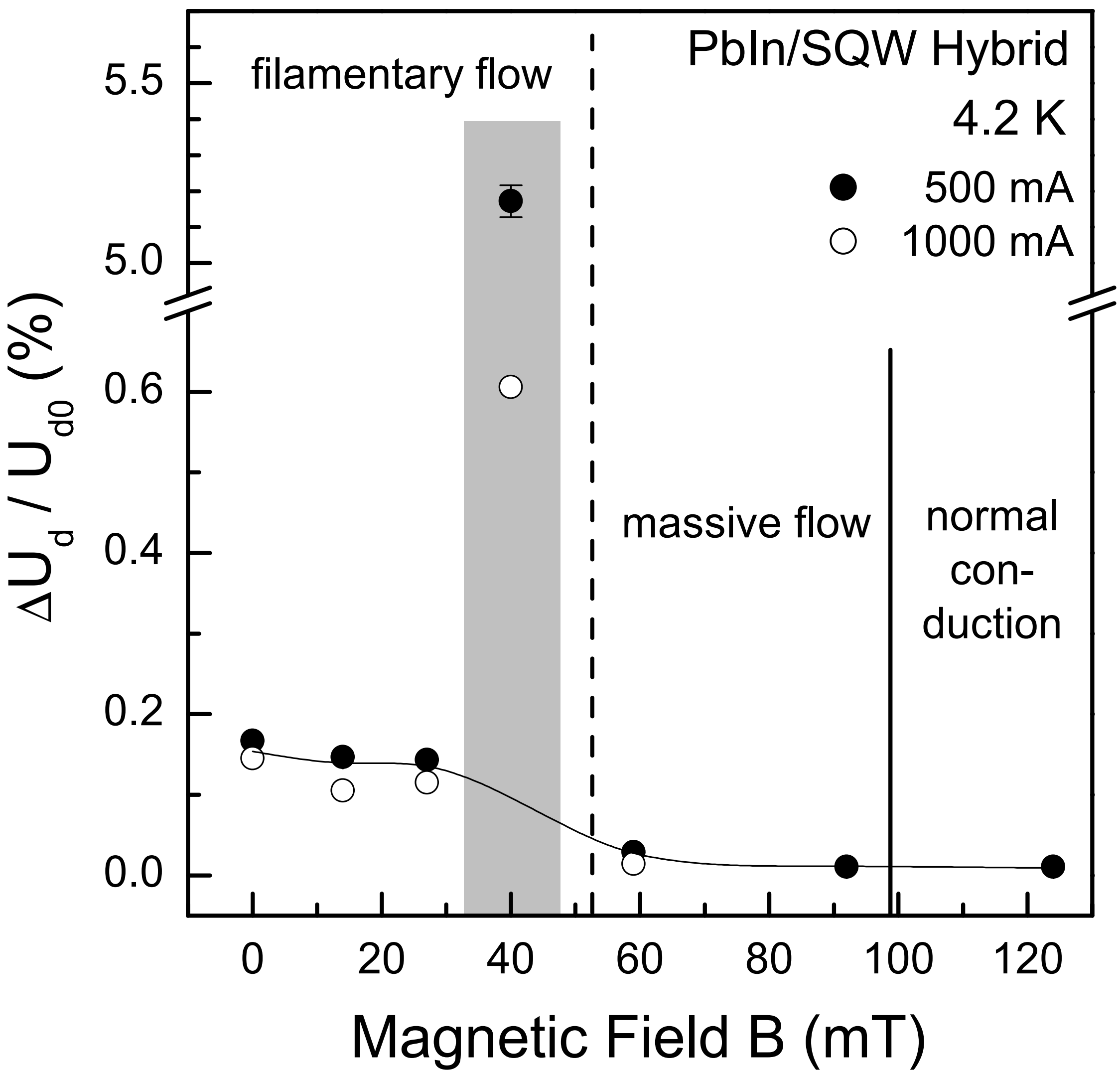

Fig. 4 Danckwerts et al.